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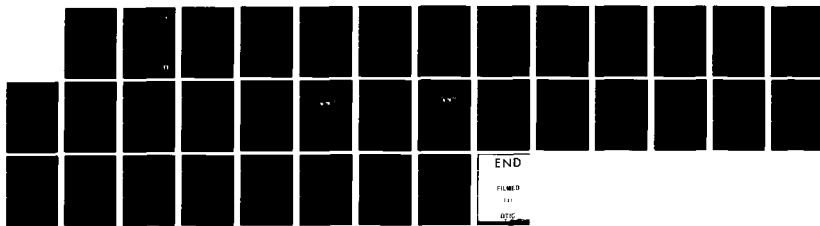HANSCOM AFB MA   P TATTELMAN ET AL. 17 NOV 82
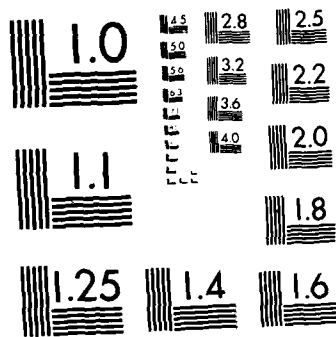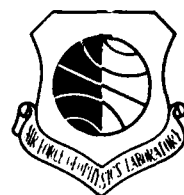UNCLASSIFIED   AFGL-TR-82-0357 AFGL-TR-82-0357   F/G 12/1   NL

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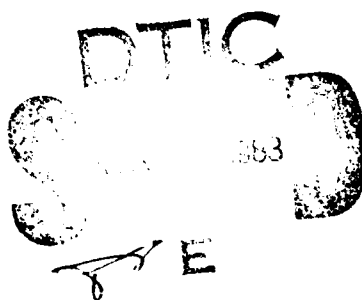
PAUL TATTELMAN
DONALD D. GRANTHAM

17 NOVEMBER 1982

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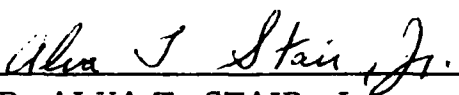
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A search for information on short-duration precipitation rates uncovered several sources of data, primarily for North America and Europe. However, the data available, especially for 1-min rainfall rates, are insufficient to permit direct calculation of precipitation-rate frequency distributions for all but a few locations in the world. Since these statistics are needed for a variety of applications, researchers developed models that can be used to estimate 1-min rainfall-rate distributions. Some require climatic data,

20. Abstract (Continued)

while others divide the globe into regions, each of which is associated with a representative distribution. A survey of the available data and a comparison of models for determining short-duration precipitation rate distributions is presented, with particular emphasis on 1-min rates.

Preface

We would like to thank Mr. Arthur Kantor (AFGL) for his support and advice, Lt. Scott Gibbons (ETAC) for his timely contribution of estimates from clock-hour data, and Mrs. Helen Connell for typing this report.

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I. INTRODUCTION

In the past 10 to 15 years, there has been increasing demand for information on short-duration precipitation rates (intensities averaged over intervals of 5 min or less). Primary interest is in 1-min intensities, commonly referred to as "instantaneous" rates. Knowledge of the frequency-distribution of short-duration rates is important to the design and operation of many types of equipment. Precipitation, especially at heavier intensities, attenuates microwave signals of Air Force systems used in satellite detection and tracking, communications, air traffic control, reconnaissance, and weaponry. Erosion due to rain is important to the design and operation of helicopter rotor blades, leading edges of aircraft and missiles, and fuses on airborne ordnance. Intense rainfall can cause jet engines to malfunction and can penetrate protective coverings on exposed electronic and mechanical materiel.

Rainfall statistics have been collected at thousands of locations worldwide, for more than 100 years in many instances. However, data collection was oriented toward agricultural and hydrological purposes, for which monthly, daily, and less commonly, 3- and 6-hourly totals were collected. Rates for 3 hr down to 1 min are available for many stations in the United States, but for very few

stations elsewhere in the world. Clock-hour data (totals on the hour every hour) are also available for numerous stations in the United States, some stations in Europe, but only a few stations elsewhere.

Most rain gauges in every day use do not have adequate resolution to measure short-duration rates. Much of the meager amount of data that are available were collected during special field programs conducted for brief periods of time (for example, 1 to 3 years). Therefore, researchers have devised models for estimating the frequency distribution of instantaneous precipitation rates by relating the available data to climatological data (for example, mean precipitation, mean temperature, etc.) that are available for most observation sites in the world.

This report presents a review of techniques for estimating the frequency distribution of instantaneous rates at a point, and an evaluation of the limits of their applicability. Some authors of these techniques use the term rainfall (or rainfall rate) instead of precipitation. The use of either term in this report implies the inclusion of the melted equivalent of frozen precipitation.

2. BACKGROUND

There are three major, readily available sources of short-duration precipitation data. The largest is published by The National Oceanic and Atmospheric Administration (NOAA[1]). It contains the highest annual intensities for intervals of 5 to 180 min, for 30 years, at approximately 250 stations in the U.S. Lin[2] and Lee[3] developed methods to use these data for estimating the distribution of short-duration precipitation rates at the cities for which they are available. The other two sources[4,5] published (under contract with USAF) an extensive amount of data and analyses for rates of 4 min or less at four networks and at numerous point locations. One-minute distributions were provided for 13 of these locations,

1. National Oceanic and Atmospheric Administration (1980) Climatological Data National Summary, in annual issues since 1950, U.S. Dept. of Commerce.

2. Lin, S. H. (1977) Nationwide long-term rain rate statistics and empirical calculation of 11-GHz microwave rain attenuation, Bell System Tech. J. 56(No. 9):1581-1604.

3. Lee, W. C. Y. (1979) An approximate method for obtaining rain rate statistics for use in signal attenuation estimating, IEEE Trans. Antennas Propag. AP-27(No. 3):407-413.

4. Sims, A. L., and Jones, D. M. A. (1973) Climatology of Instantaneous Precipitation Rates, AFCRL-TR-73-0171, Final Report, Contract F19628-72-C-0052, Illinois State Water Survey, Urbana, Ill., AD 760785.

5. Jones, D. M. A., and Sims, A. L. (1971) Climatology of Instantaneous Precipitation Rates, AFCRL-TR-72-0430, Final Report, Contract F19628-69-C-0079, Illinois State Water Survey, Urbana, Ill., AD 749878.

seven in the United States, three in Europe, and three in the Tropics. A potentially extensive source of data for the U.S. is discussed by Bodtmann and Ruthroff.[6] They present a method for analyzing 1-min rainfall rate distributions from weighing rain gauge recordings, a large number of which are available from the National Weather Service. Results are presented for a 5-year period at 20 U.S. cities.

Watson et al[7] conducted a survey of 25 European countries to determine the availability of short-duration rainfall data. Their summary of the results reveals eight countries that have instantaneous data for at least one site, and 19 countries that have collected either 5-min or hourly rates. These sources hold promise for future studies of short-duration rates in Europe. Segal[8] analyzed original rainfall recorder charts for 47 Canadian stations. The results are in the form of curves of long-term probability of exceeding instantaneous rainfall rates of 10 to 300 mm/hr for each location.

Some researchers (for example, Freeny and Gabbe[9]) present data and analysis of short-duration rates for individual rain-gauge networks. These provide interesting statistics on the temporal and spatial variability of short-duration rainfall. Other researchers utilized radar to measure precipitation rates, but these are not accurate enough for most applications. The magnitude and diversity of the studies on short-duration precipitation preclude discussing the vast majority of them here. However, Huff[10] and Court[11] present an excellent overview of literature on precipitation research. The emphasis of our report is on empirical models or techniques for estimating the frequency distribution short-duration precipitation at a point based on rain-gauge observations over longer time intervals.

6. Bodtmann, W.F., and Ruthroff, C.L. (1976) The measurement of 1 min rain rates from weighing raingage recordings, J. Appl. Meteorol. 15:1160-1166.

7. Watson, P.A., Sathiaseelan, V., and Potter, B. (1981) Development of a climatic map of rainfall attenuation for Europe, Interim Report for European Space Agency, ESTEC Contract No. 4162/79/NL/DG(SC), Report 300, 134 pp.

8. Segal, B. (1979) High Intensity Rainfall Statistics for Canada, Communications Research Center Report No. 1329-E, Dept. of Communications, Ottawa, Canada, 124 pp.

9. Freeny, A.E., and Gabbe, J.D. (1969) A statistical description of intense rainfall, Bell System Tech. J. 48:1789-1851.

10. Huff, F.A. (1974) Statistics of precipitation, J. Rech. Atmos., pp. 73-88.

11. Court, A. (1979) Precipitation research, 1975-1978, Rev. Geophys. Space Phys., Hydrology 17(No. 6):1165-1175.

3. ESTIMATING SHORT-DURATION RATES FROM LONGER-DURATION MEASUREMENTS

The paucity of measurements of short-duration rainfall has prompted studies of the distribution of short-duration intensities within a larger interval of time, usually 1 hr. A very early study by Bussey[12] showed how the instantaneous rate distributed itself around the mean hourly rate. He found that for Washington, D. C. about 20 percent of an hour the rate was a "trace" or less, 35 percent of the time the mean hourly rate was exceeded, and "to exceed it by five or six times for a few minutes was a fairly common occurrence." Briggs and Harker[13] examined data from special gauges at Winchcombe, England to obtain the distribution of 2-min intensities associated with various ranges of clock-hour totals. Their results are in general agreement with Bussey,[12] and suggest that they may be generally applicable to showery precipitation. On a broader scale, Davis and McMorrow[14] used actual 1- and 4-min rainfall measurements at 13 locations to develop relationships between clock-hour and short-duration rates.

Due to the importance of instantaneous rates for some applications, researchers have studied the relationship of these rates to 5-min rates. For example, Hershfield[15] used statistical techniques to estimate extreme 1-min rates from the 5-min rates published by NOAA.[1] Pinkayan and Ketratanaborvorn[16] derived an exponential equation relating 1-, 2-, 3-, and 4-min rates to 5-min rates.

These techniques are most useful for the locations (mostly in Europe and North America) for which clock-hour or other similarly comprehensive precipitation measurements are available. For deriving frequency distributions, models that utilize data in the form of monthly or annual means of temperature and precipitation, number of days with precipitation, etc., have been devised.

---

12. Bussey, H. E. (1950) Microwave attenuation statistics estimated from rainfall and water vapor statistics, Proc. IRE 38:781-785.

13. Briggs, J., and Harker, J. A. (1969) Estimates of the duration of short-period rainfall rates based on clock-hour values, Meteorol. Mag. 98:246-252.

14. Davis, A. R., and McMorrow, D. J. (1976) Stochastic Models for Deriving Instantaneous Precipitation Rate Distributions, U. S. Air Force, Air Weather Service Tech Report AWS-TR-76-263, AD A036493, USAFETAC, Scott AFB, Ill.

15. Hershfield, D. M. (1972) Estimating the extreme-value 1-minute rainfall, J. Appl. Meteorol. 11:936-940.

16. Pinkayan, S., and Ketratanaborvorn, T. (1975) Measurement and analysis of very short duration rainfall, Hydrological Sciences - Bulletin - des Sciences Hydrologiques, Bangkok, Thailand, XX:87-91.

4. MODELS FOR ESTIMATING INSTANTANEOUS PRECIPITATION RATE DISTRIBUTIONS

Five models are presented in this section, of which four are used to estimate annual instantaneous precipitation-rate distributions. The fifth model estimates monthly instantaneous rate distributions. Three models require input of climatic data, and two require only identification of the applicable region.

4.1 Rice-Holmberg Model (R-H)

The model proposed by Rice and Holmberg[17] estimates the percentage of an average year that t-min surface rainfall rates exceed a given value (for t = intervals of 1 min to 1 day). For 1-min rates, the model uses two parameters for a specific location, the mean annual precipitation (M), and the ratio of annual thunderstorm rainfall to the total annual rainfall (β). For t > 1 min, an additional parameter, the mean annual number of days with precipitation (D) $\geq$ 0.25 mm (0.01 in.) is also used. M is available for almost all meteorological observation sites, and the authors provide it as contours on a world map. The ratio β is not readily available and must be calculated from meteorological data. The authors have done this without describing the procedure, and present the results as contours on a world map. The number of days with precipitation is generally available, but minimum threshold values (0.01 in, 1 mm, etc.) vary from country to country.

The model was developed using data collected in the U.S., including extreme short-duration precipitation published by NOAA[1] for the years 1951-1960, which was extrapolated to estimate 1-min rates. World contour maps of M and β require interpolation that is very difficult in areas where isolines are closely spaced. These are major shortcomings of the model.

4.2 Dutton-Dougherty Model (D-D)

This model (Dutton et al[18]) is an adaptation of the R-H model to Europe and it utilizes the same input parameters: M, β, and D. The D-D modification to the R-H model facilitates error analysis of the predicted distribution, and simplifies procedures for estimating rain rates for a specific percentage of a year. The

17. Rice, P.L., and Holmberg, N.R. (1973) Cumulative time statistics of surface - point rainfall rates, IEEE Trans. Commun. COM-21(No. 10): 1131-1136.

18. Dutton, E.J., Dougherty, H.T., and Martin, R.F., Jr. (1974) Prediction of European Rainfall and Link Performance Coefficients at 8 to 30 GHz, Institute for Telecommunication Sciences, U.S. Dept. of Commerce, Boulder, Colo., AD/A-000804.

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authors also present a method for calculating β for a specific location and for estimating year-to-year variations. Differences in the distributions between the R-H and D-D models are slight.

Rainfall data for 249 stations were grouped into ten climatic rainfall zones covering Europe. Values of M, β, and D were determined for each station and averaged for the stations in each zone. These were used to construct nomograms of rainfall rate versus the percent of time the rate is exceeded in an average year, for rate-averaging times of 1, 5, 30, 60, 360, and 1440 min (1 day), for each of the ten zones. The distribution for zone 2, which includes the British Isles and western France, is shown in Figure 1. Contour maps of M, β, and D for Europe, provided by the authors, can be used to estimate distributions at specific sites. Contour maps for Europe of 1-min rainfall rates for 1, 0.1, and 0.01 percent of a year from the report are shown in Figure 2.

Subsequently, Dutton and Dougherty[19] calculated input parameters to the D-D model for 305 U.S. weather stations based on 30 years of data. The results are presented as contour maps of 1-min rainfall rates predicted for 1, 0.1, and 0.01 percent of a year in the U.S. (Figure 3)

4.3 Crane Model (Cr)

Crane[20] processed seven years of excessive precipitation data for 15 stations in New England and eastern New York from the annual reports published by NOAA.[1] He found that the mean and variance of the annual extremes were similar to the mean and variance for 24 years at one of the stations (Boston). The mean of the annual extreme rates was 100 mm/hr with a standard deviation (SD) 35 mm/hr in the 15-station sample. The mean and SD for Boston were 91 mm/hr and 44 mm/hr. He felt that his results warranted the use of climatically uniform regions, and further developed a global rain-rate climate model (Crane[21]). In it the world is divided into eight regions (Figure 4) based on total rain accumulation, and the number of thunderstorm days from maps published by Landsburg.[22] The U.S. is covered by five regions; but one of them is further divided into three subregions (Figure 5). Crane obtained additional guidance from the Köppen world

19. Dutton, E.J., and Dougherty, H.T. (1979) Year-to-year variability of rainfall for microwave applications in the U.S.A., IEEE Trans. Commun. COM-27(No. 5):829-837.

20. Crane, R.K. (1977) Prediction of the effects of rain on satellite communication systems, Proc. IEEE 65:456-474.

21. Crane, R.K. (1980) Prediction of attenuation by rain, IEEE Trans. Commun. COM-28(No. 9):1717-1733.

22. Landsburg, H.E., Ed. (1974) World Survey of Climatology, Vols. 1-15, Elsivier Pub. Co., Amsterdam, The Netherlands.
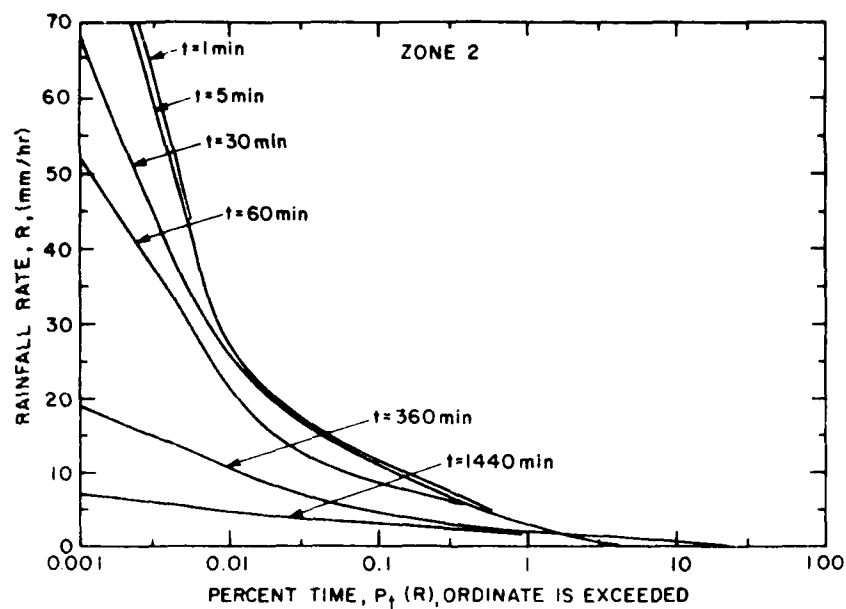
Figure 1. The Distribution of Rainfall Rates of t-min Duration
in European Climatic Zone 2 (From Dutton et al[18])
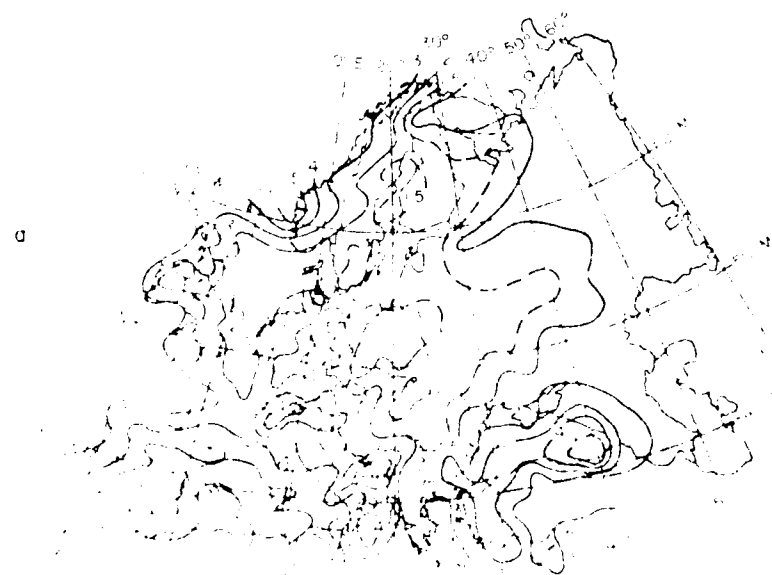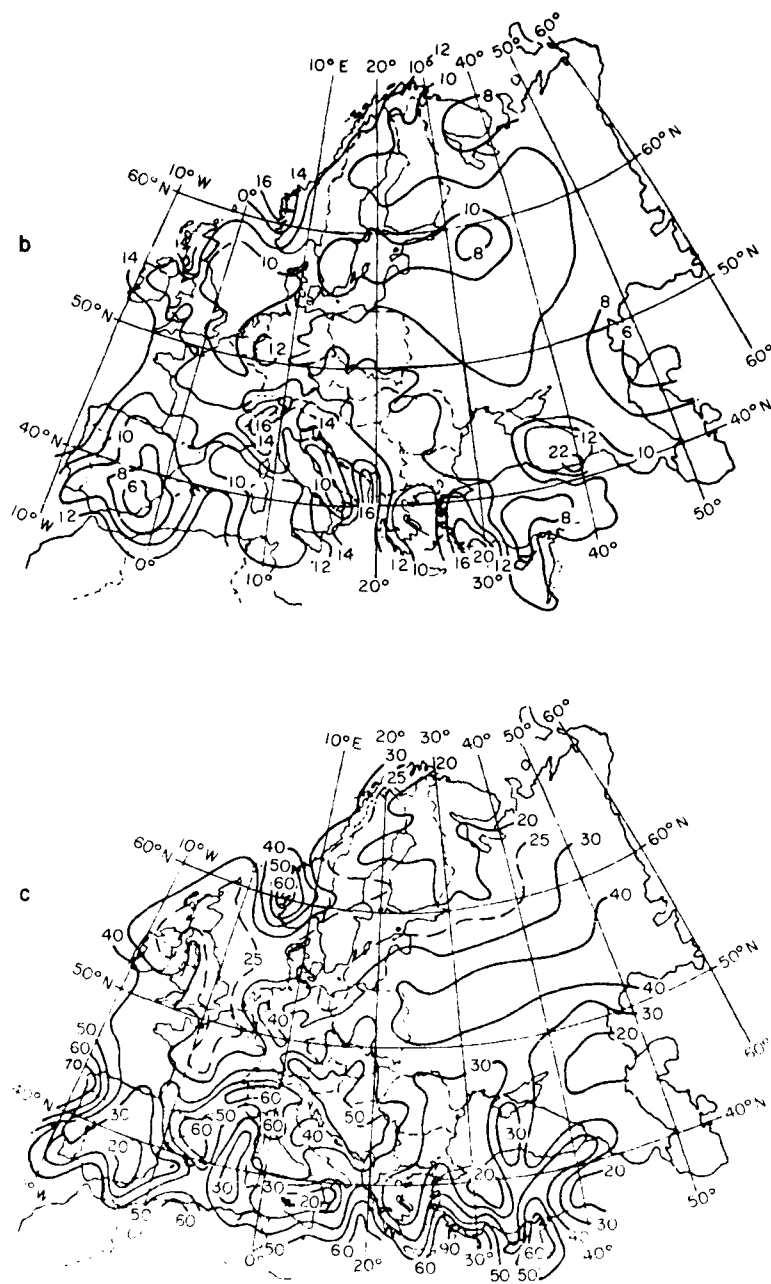
Figure 2. Estimates of the 1-min Rainfall Rates (mm/hr) in Europe Exceeded in a Year: (a) 1 Percent of the Time, (b) 0.1 Percent of the Time, and (c) 0.01 Percent of the Time (From Dutton et al[18]) (Continued)

Figure 3. Estimates of the 1-mm Rainfall Rates (mm/hr) in the U.S. Exceeded in a Year: (a) 1 Percent of the Time, (b) 0.1 Percent of the Time, and (c) For 0.01 Percent of the Time (From Dutton and Dougherty[19])

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c

Figure 3. Estimates of the 1-min Rainfall Rates (mm/hr) in the U.S.
Exceeded in a Year: (a) 1 Percent of the Time, (b) 0.1 Percent of the
Time, and (c) For 0.01 Percent of the Time (From Dutton and
Dougherty[18]) (Continued)

climate classification. Boundaries were adjusted to accommodate variations in
terrain, predominant storm type and motion, general atmospheric circulation,
and latitude. Satellite and precipitation frequency data were used to extend the
rain climate regions over the oceans. Feldman[23] presents an elaborate expansion
of the model for ocean areas.

The measured instantaneous rain-rate distributions that were available for
each of the seven regions and three sub-regions were pooled to construct the rain-
rate distributions (Table 1). No data were available for Region A, and the author
does not explain how its distribution was derived.

23. Feldman, N.E. (1979) Rain Attenuation Over Earth-Satellite Paths, Final
    Report, Contract N00039-79-C-0136 for Naval Electronic Systems
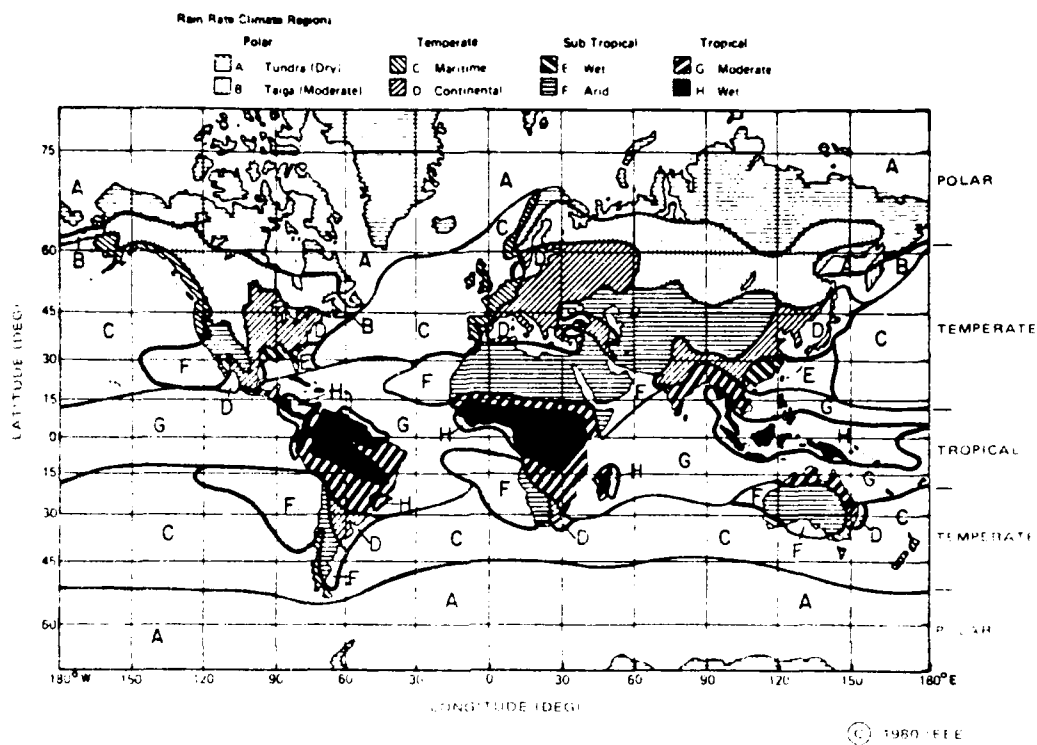   Command, Science Applications, Inc., AD A075390.
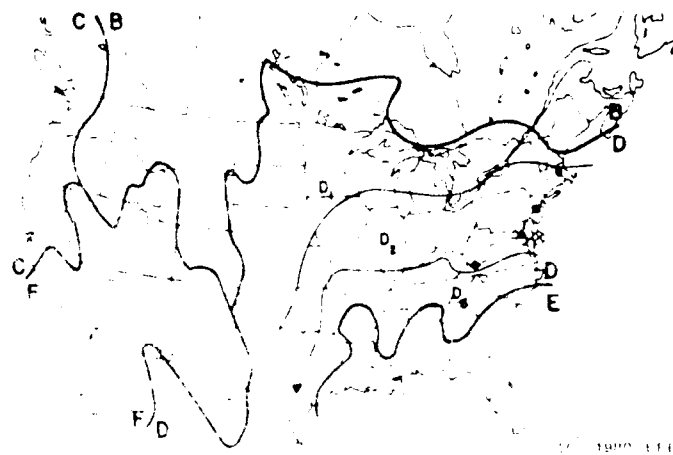
Figure 4. Global Rain Rate Climate Regions (From Crane[21])

Figure 5. U.S. Rain Rate Climate Regions
(From Crane[21])

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Table 1. Point Rain Rates (mm/hr) Versus Percent of Year Rain Rate is Exceeded for the Regions Shown in Figures 4 and 5 (From Crane[21])

Percent of Year	Time	Rain Climate Region									
		A	B	C	D_1	D_2	D_3	E	F	G	H
0.001	5 m	28	54	80	90	102	127	164	66	129	251
0.002	10 m	24	40	62	72	86	107	144	51	109	220
0.005	26 m	19	26	41	50	64	81	117	34	85	178
0.01	53 m	15	19	28	37	49	63	98	23	67	147
0.02	1.7 hr	12	14	18	27	35	48	77	14	51	115
0.05	4 hr	8.0	9.5	11	16	22	31	52	8.0	33	77
0.1	9 hr	5.5	6.8	7.2	11	15	22	35	5.5	22	51
0.2	18 hr	4.0	4.8	4.3	7.5	9.5	14	21	3.2	14	31
0.5	1.8 d	2.5	2.7	2.8	4.0	5.2	7.0	8.5	1.2	7.0	13
1.0	3.6 d	1.7	1.8	1.9	2.2	3.0	4.0	4.0	0.8	3.7	6.4
2.0	7.3 d	1.1	1.2	1.2	1.3	1.8	2.5	2.0	0.4	1.6	2.8
Number of Station Years of Data		0	25	44	15	96	18	12	20	2	11

4.4 Jones-Sims Model (J-S)

Jones and Sims[24] utilized 1- and 4-min rainfall data from 19 locations in the Northern Hemisphere to describe the rainfall rate-frequency relationships for four of the five rain climate regions, worldwide, used by Herbstritt.[25] This broad classification system (Figure 6) does not include polar regions for which rainfall rates are presumably not of importance for most applications. Figure 7 shows the curves for the four regions derived by averaging the frequencies for the individual stations within each of the regions.

4. Jones, D.M.A., and Sims, A.L. (1978) Climatology of instantaneous rainfall rates, J. Appl. Meteorol. 17(No.5):1135-1140.

2. Herbstritt, R.L. (1976) Rain Climate Considerations for Domestic Satellites - Continental U.S., Report No. R-7501, Federal Communications Commission, Office of the Chief Engineer, Washington, D.C., 5 pp.
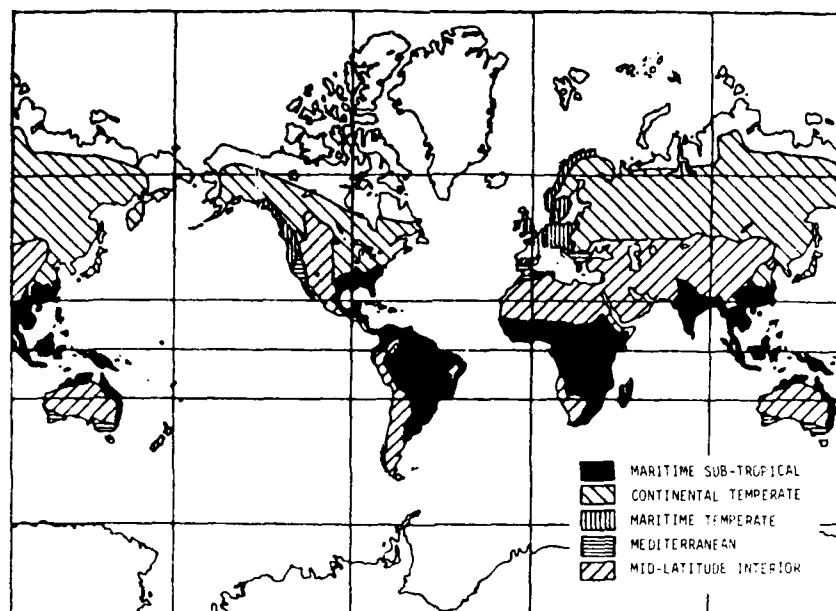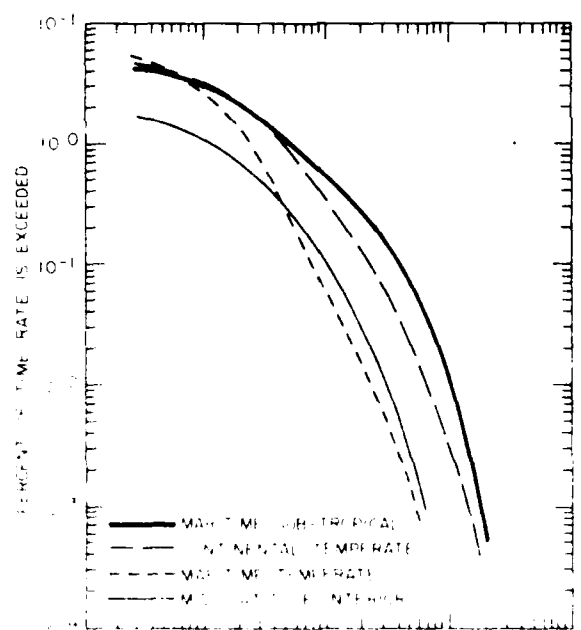
Figure 6. World Rain Climates Used by Herbstritt[25]

Figure 7. Rainrate Time-Duration Relation-
ships for Four Rain Climates (From Bartz
and Sims[24])

The obvious shortcomings of the J-S model are the mixing of 1- and 4-min data, and the use of extensive regions. Resolution is poor when information for individual locations is required.

4.5 Lenhard Model (Le)

The only method we found that can be used to estimate monthly rainfall rate statistics was developed by Lenhard.[26] He used data on 1-min rainfall rates for 13 stations, published by Jones and Sims[5] and Sims and Jones,[4] and developed a model for estimating instantaneous rainfall rates equalled or exceeded 2.0, 1.0, 0.5, 0.1, 0.05, and 0.01 percent of the time during a month from readily available climatological data. The model is of the form

$$R_p = A_p + B_p I + C_p T \qquad (1)$$

where R_p is the precipitation rate (mm/min) equalled or exceeded p percent of the time during the month, I is a precipitation index (the ratio of mean monthly precipitation and the number of rainy days), and $T(^\circ F)$ is the monthly mean temperature. A_p, B_p, and C_p are coefficients that depend upon the exceedance probability (p). Each coefficient is given by

$$K = \alpha + \beta \ln p + \gamma \ln^2 p \qquad (2)$$

where K is the coefficient (A_p, B_p or C_p) and α, β, and γ are least-squares regression coefficients.

Separate sets of equations were derived for precipitation indices based on days with 0.01 in., 0.1 in., or 1 mm or more to define a rainy day. Another threshold value to define a rainy day is a "trace," but differences between the number of days with this amount and 0.01 in. or more were found to be slight. Table 2 gives the coefficients to be used in Eq. (2) for each of the three definitions of a day with rain. Also, coefficients are presented separately as derived using data from all 13 stations in the study, from the ten extra-tropical stations, and from the three tropical stations. As an example, to estimate the rainfall rate exceeded 0.1 percent of the time at Paris in July, Eq. (1) becomes

For an index of 5.8 mm per rain day based on days with 1 mm or more, and a mean temperature of 67.5°F, the equation yields an estimate of 0.86 mm/min.

Table 2. Coefficients to Produce Estimating Equations for the Lenhard Model

K	All Regions			Tropical		Extra-tropical		
	A_p	B_p	C_p	A_p	B_p	A_p	B_p	C_p
Index based on days with 0.01 in. or more of rain								
α	-0.09605	0.00911	0.00143	0.00378	0.01571	0.01256	0.00578	-0.00032
β	0.19444	-0.00904	-0.00312	-0.07436	-0.01275	0.10626	-0.00666	-0.00157
γ	-0.02245	0.00028	0.00075	0.02126	0.00090	-0.03071	0.00028	0.00092
Index based on days with 0.10 in. or more of rain								
α	-0.10308	0.00496	0.00184	-0.01943	0.01287	0.01642	0.00334	-0.00033
β	0.20257	-0.00555	-0.00339	-0.06976	-0.00976	0.10020	-0.00447	-0.00138
γ	-0.02278	0.00022	0.00075	0.00880	0.00128	-0.03045	0.00013	0.00098
Index based on days with 1 mm or more of rain								
α	-0.09860	0.00695	0.00164	-0.00563	0.01491	0.01708	0.00468	-0.00038
β	0.19739	-0.00752	-0.00321	-0.07037	-0.01188	0.09872	-0.00599	-0.00142
γ	-0.02257	0.00029	0.00074	0.01632	0.00112	-0.03047	0.00021	0.00092

Lenhard cautions that the model cannot be extended below the input data, (that is, mean temperature <22°F and index values <2 mm/day). In fact, some internal inconsistencies were found at index values below 10 mm/day and temperatures below 40°F. Rates should decrease with an increase in the probability of exceedance. To determine if the equations are applicable to a location that is either very cold or very arid or both is to calculate rates for all exceedance probabilities. If they are consistent with each other, they are acceptable. If they are consistent but a negative rate shows up at the higher exceedance probabilities (for example, 1 or 2 percent), it could indicate that it doesn't rain that often in that month.

4.6 Comparisons

The D-D model is a modification of the R-H model, and actual differences in the distributions calculated using them are slight (Dutton et al[18]). One of the input parameters for both models is the ratio of thunderstorm rain to total rain

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at a location. Dutton et al[18] presents an expression to calculate this ratio, but
it requires the highest monthly precipitation observed in 30 consecutive years of
data. Few stations outside of North America and Europe have recorded such data.
However, a world map of the ratio is provided by Rice and Holmberg.[17]

The Cr and J-S models provide instantaneous rate distributions for a given
percent of a year for regions delineated for this purpose. Distinct advantages
of the Cr model are the greater number of regions used and the greater clarity
of regional boundaries (see Figures 4 to 6). A descriptive comparison of the
models is provided in Table 3.

A comparison of estimates using the R-H, D-D, Cr, and J-S models with
observed values for U.S. cities is given in Table 4. The observed values were
taken from the distributions derived from five years of original records at each
city by Bodtmann and Ruthroff.[6] These data were not used in the development of
any of the models. R-H model estimates were made using M from long-term
climatic data instead of the world contour map for M provided with the model.
D-D model estimates were made using their contour map for the U.S. [Figure 3(c)].
The best estimates, as indicated in Table 4 by the root-mean-square departures,
were made using the Cr model, followed by the D-D, R-H, and J-S models.

The Le model was not compared to the others in Table 4 because it produces
estimates of instantaneous rates on a monthly basis. Although these statistics are
probably more useful than annual distributions for many applications, no other
monthly or seasonal global models were found. At AFGL, development of an
improved model for estimating monthly distributions is being completed. A report
on the model will be released in the near future.

5. DERIVING INSTANTANEOUS PRECIPITATION RATE
STATISTICS FROM CLOCK-HOURLY DISTRIBUTIONS

Four models are presented in this section. Two use clock-hour data to derive
the distribution of instantaneous rates, and two can be used to derive clock-hour
distributions.

5.1 Models for Deriving Instantaneous Distributions

Davis and McMorrow[14] derived tables of clock-hour rate intervals versus
instantaneous rate intervals for six locations, and versus 4-min rates for seven
other locations, worldwide. The tables give the percent contribution of the short-
duration rate within each of nine specified intervals for each clock-hour rate
interval The location for which the short-duration precipitation rate distribution
is required must be compared with the stations in the report. The tables for the

Table 3. Comparison of Models for Estimating Instantaneous Precipitation Rates

Model	Input Parameters	Output	Where Applicable	Advantages	Disadvantages
R-H	1. Mean annual precipitation 2. Ratio of thunderstorm rain to total rain	Percentage of year that 1-min sfc rainfall rates exceed a given value	Worldwide? The authors used U.S. data and conclude that results are applicable for the U.S. However, they provide global maps of the input parameters and compare model output with four stations outside the U.S. implying global applicability.	Distributions of the frequency of 1-min rates can be calculated for individual locations	1. Based only on U.S. data 2. World contour maps that are furnished to determine inputs have poor resolution
D-D	Same as R-H model	This is a modification of the R-H model that facilitates estimating 1-min rainfall rates exceeded vs percent of an avg year	Worldwide, but applied only to data from Europe and the U.S. (presented in separate reports). Can be extended to any location in the world for which input parameters can be calculated.	1. Rainfall rate for a given percent of one year can be calculated for individual locations with climatic data 2. Contour maps of input parameters have better resolution for applicable regions than R-H model 3. Includes a method for calculating the ratio of thunderstorm rain to total rain for a specific location that is not included in R-H model	Calculation for an individual location requires the highest monthly precipitation in 30 consecutive years, which is not readily available outside of Europe and N. America
Cr	World is divided into eight regions of "homogeneous" rainfall rates (part of the U.S. is further divided into three subregions)	Distribution of 1-min sfc rainfall rates vs percent of year the rate is exceeded for each region	Worldwide	1. Applicable worldwide 2. Addresses year-to-year variability and variability of rainfall rates within each region	Large variations in rainfall rates for individual stations within regions
J-S	World is divided into five regions	Same as Cr model, however, distributions are presented for only four of the five regions	Worldwide except polar regions and one of the five climatic regions	Includes example of the dispersion of the station distributions grouped to represent a climatic region	1. Regions are too extensive and precision of estimates for individual locations is low 2. 1- and 4-min data were mixed to derive the distributions
	1. Mean monthly precip 2. Mean monthly no. of rainy days based on one of three threshold values 3. Mean monthly temp	Estimate of 1-min rainfall rates equalled or exceeded for a given percent of a month	Worldwide	1. It is the only available model that addresses the distribution of rates on a monthly basis 2. Estimates can be made for individual locations with climatic data	1. Not valid for months with mean temp < 0°? 2. Not valid in arid locations 3. Erroneous estimates may occur for months with mean temp < 4.4°? or where avg daily precip < 1.5 mm

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Table 4. Comparison of Model Estimates of Instantaneous Rates With Those Observed at Nine U.S. Cities. Departures from observed values are given in parenthesis

Location	Rate for 0.01 Percent of an Avg Year (mm/hr)				
	Observed	R-H	D-D	Cr	J-S
Atlanta, Ga.	69	93(+24)	92(+23)	63(-6)	100(+31)
Bismarck, N.D.	41	30(-11)	35(-6)	37(-4)	65(+24)
Buffalo, N.Y.	48	53(+5)	48(0)	43*(-5)	65(+17)
Columbus, Ohio	56	62(+6)	55(-1)	49(-7)	65(+9)
Dallas, Tex.	73	85(-12)	75(+2)	56*(-17)	100(+27)
Memphis, Tenn.	64	93(+29)	80(+16)	63(-1)	100(+36)
Miami, Fla.	111	115(+4)	115(+4)	98(-13)	100(-11)
Milwaukee, Wis.	52	56(+4)	55(+3)	43*(-9)	65(+13)
Newark, N.J.	50	48(-2)	60(+10)	49(-1)	65(+15)
Root-mean-square departures		14.1	19.3	8.6	22.2

These estimates are the average for the two regions on which these locations border.

station most climatically compatible with the location of interest would be used to derive the distribution. Unfortunately, instantaneous rates are provided for only six locations, and the class intervals for the percentage contribution of the instantaneous rates for each clock-hour rate interval are quite large (for example, clock-hour rate 1 mm/hr, rate 1 to 12 mm/hr).

In a report by Hershberg et al. present a method for estimating 1 to k-hour rates from hourly rate observations. The distribution of clock-hour rates at a location is then used to derive the distribution of instantaneous rates in a manner very similar to that of Bussey and Norris. It is necessary to estimate the ratio for the interval rate relation and other intermediate equations. The authors apparently restricted their attention to precipitation at the States, and they developed an empirical relation ...

Estimates of instantaneous rates from observed clock-hour rates using the Davis and McMorrow tables, and from Huschke's table that combines all the Davis and McMorrow data, were determined for 0.01 percent of a year at the nine U.S. cities in Table 4. These estimates, provided by the USAF Environmental Technical Application Center (ETAC), are given in Table 5 along with observed values for each city from Table 4. ETAC made the Davis and McMorrow estimates using the Urbana, Ill., table for all locations in Table 5, except Memphis and Miami, for which the Franklin, N.C., and Miami tables, respectively, were used. Tables to estimate 1-min rates are also available for Majuro Atoll, Marshall Islands; Woody Island, Alaska; and Island Beach, N.J. The Island Beach table would seem the logical choice to make the estimate for Newark in Table 5. However, Davis and McMorrow[14] incorporate an internal check to determine the applicability of the analog model to the rain-rate statistics for the station being modeled. They indicate that the mean precipitation at a location correlated best with the lower 35th percentile integrated rainfall amount calculated from the estimated instantaneous rate distribution. The 35th percentile value for Newark is 110.5 cm (43.5 in.), and 118.4 cm (46.6 in.) using the Urbana and Island Beach models, respectively. Since the actual annual average precipitation

Table 5. Comparison of Instantaneous Rates Estimated From Clock-hour Rates With Those Observed at Nine U.S. Cities. Departures from observed values are given in parentheses

Location	Rate for 0.01 Percent of an Avg Year (mm/hr)		
	Observed	Davis & McMorrow	Huschke
Atlanta, Ga.	69	71(+2)	72(+3)
Bismarck, N.D.	41	38(-3)	35(-6)
Buffalo, N.Y.	48	47(-1)	44(-4)
Columbus, Ohio	56	54(-2)	52(-4)
Dallas, Tex.	73	69(-4)	72(-1)
Memphis, Tenn.	64	65(+1)	79(+15)
Miami, Fla.	111	109(-2)	102(-9)
Milwaukee, Wis.	52	54(+2)	51(-1)
Newark, N.J.	50	58(+8)	54(+4)
Root-mean-square departures		3.4	6.7

for Newark is 105.4 cm (41.5 in.) the Urbana model was used. The rate estimated for 0.01 percent of the year using the Island Beach model is 60 mm/hr.

The root-mean-square departures from the observed values using the Davis and McMorrow, and Huschke models, given in Table 5, are smaller than for the models in Table 4. These results justify the use of clock-hour data, when available, to estimate instantaneous rate distributions. When not available, the models in the next section can be used to estimate clock-hour distributions.

5.2 Models for Deriving Clock-Hour Distributions

Using clock-hour data for four U.S. sites, Russak and Easley[28] found good linear correlations between a climatological index (CI) and the number of hours per year that specified hourly rates are exceeded. CI is simply the ratio of the mean annual precipitation, in inches, to the mean annual number of rainy days. They determined that the regression lines of CI versus the hours per year (H_r) the rate (r) is exceeded comprised a family of lines that could be expressed by the relationship

$$H_r = m(CI - a) , \tag{3}$$

where m is the slope of the regression line for rate r, and a is the x-axis intercept of the regression line for rate r. It should be noted that five threshold values to define a rainy day are in general international use; trace, 0.1 mm, 1 mm, 0.01 in., and 0.1 in.

Russak and Easley provide curves of m and a versus precipitation rate, so the user needs only the mean annual precipitation and number of rainy days at a location to use the model. By determining the number of hours per year of rainfall in the interval between two rates for a sufficient number of intervals, it is possible to construct a cumulative frequency distribution for a location. This was done by the authors for Naples, Italy, and the results compare favorably with the frequency distribution from actual clock-hourly data. They note, however, that the method is not valid in certain climatic regions. For example, erroneous results are likely in arid locations, areas with strong monsoonal or orographic control, or regions where convective precipitation is very predominant. The model accuracy probably suffers because it does not address differences in the threshold rainfall amount used to define a rainy day.

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28. Russak, S. L., and Easley, J. W. (1958) A practical method for estimating rainfall rate frequencies directly from climatic data, Bull. Am. Meteorol. Soc. 35(No. 9):469-472.

Another model for estimating the annual distribution of clock-hour rates at a location was developed by Winner.[29] He used clock-hour data from 123 U.S. stations to develop nomograms that can be used to determine the number of hours per year that equal or exceed hourly rates of trace, 0.01, 0.02, 0.10, 0.25, 0.50, 1 and 2 in./hr. One of the input parameters is the ratio of the mean annual precipitation to the average annual number of days with precipitation ≥0.01 in. Another parameter in the model is called a "moisture index" for which information on potential evapotranspiration is needed. The author suggests two sources for this data.

This model was intended to overcome the geographical limitations of the Russak and Easley model. However, results compared poorly with independent data from the tropics. Therefore, the author decided to develop a different method for the tropics. Using data from 32 stations in the Panama Canal zone, he obtained best results from a linear correlation of the annual rainfall with the number of clock-hours at the various rates. The resulting relationships for estimating the mean annual number of clock-hours with precipitation equal to or greater than 0.25, 0.50, 0.75, and 1.00 in. for the tropics are provided in Figure 8.

A deficiency in Winner's approach is the threshold value of 0.01 in. for a rainy day. Although this value is used in the U.S., it is not common in most other countries. Another shortcoming is the use of only U.S. and Panama data.

6. OTHER CONSIDERATIONS

Accuracy of instruments used to record rainfall is affected by the height and size of the collector, the wind speed, and freezing conditions. Gauges also have mechanical limitations, especially at high rates. Grayman and Eagleson[30] report that these result in 5 to 10 percent error in total rainfall catch. Larger errors are likely in measurements of instantaneous rates derived from standard recording tipping or weighing bucket gages. This is due to poor resolution of the recordings down to 1 min. Special observation programs have generally utilized high-speed recorders to minimize errors in determining short-duration rates; however, these data are limited in quantity and generally available for only short periods (that is, 1 to 2 years).

29. Winner, D.C. (1968) Climatological Estimates of Clock-Hour Rainfall Rates, U.S. Air Force, Air Weather Service, Technical Report 202.

30. Grayman, W.M., and Eagleson, P.S. (1970) A Review of the Accuracy of Radar and Raingages for Precipitation Measurement, Hydrodynamics Laboratory Report No. 119, Dept. of Civil Engineering, MIT, Cambridge, Mass.
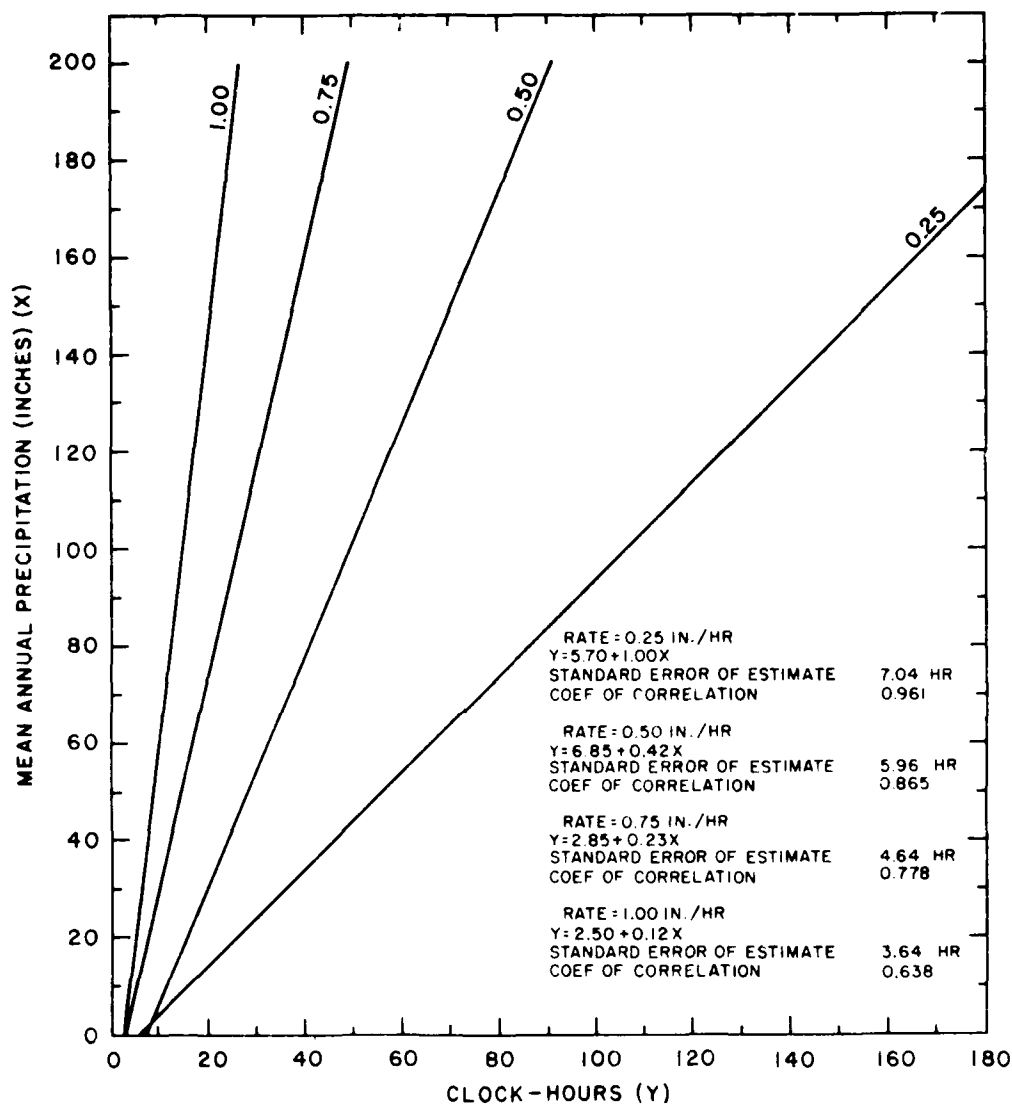
Figure 8. Nomogram for Use in Tropical Regions to Determine Mean Annual Number of Clock-hours Precipitation Equal to or Exceeding Specified Amounts Given the Mean Annual Precipitation (From Winner[29])

Year-to-year variations in the distribution of instantaneous rates observed at a location can be quite large. The models presented in this report represent the distribution to be expected on average at a point. These may not be adequate for many design problems for which a low risk is important. Annual variations are discussed for the U.S. by Dutton and Dougherty,[19] for Canada by Segal,[8] and for Europe by Dutton et al,[18] and Dougherty and Dutton.[31]

7. CONCLUSIONS

When instantaneous precipitation-rate statistics are needed for a specific point location, it is best to derive such distributions from actual measurements made continuously over a period of "many" years. Section 2 of this report refers to sources of such distributions for many locations in North America, (for example, Segal,[8] and Bodtmann and Ruthroff[6]) and potential sources of data for the U.S. (NOAA,[1] and Bodtmann and Ruthroff[6]) and Europe (Watson[7]). Distributions from observations taken during special studies for short periods, 1 to 3 years, for 13 stations worldwide were derived by Jones and Sims[5] and Sims and Jones.[4] For locations where clock-hour data are available, good estimates of instantaneous rates can be made using models by Davis and McMorrow[14] or Huschke.[27] Data for short periods, that is, less than five years, should be used with caution since they might not give a true indication of the distribution of rates during an average year.

Where distributions from actual observations are not available, they can be determined from the five models discussed in Section 4. They require the input of climatic data that are available for many observation sites worldwide. The appropriate model to use depends, in part, on the application and, in part, on the climatic data available for model input. The model developed by Lenhard[26] is the only one that can be used to estimate instantaneous rates versus frequency on a monthly basis for a specific location. The other four models can be used to determine instantaneous rates versus percent of a year. Two of them present distributions that represent all the individual locations within regions. Of these, the model developed by Crane[21] is recommended because it has a greater number of regions with more clearly-defined boundaries than the other model developed by Jones and Sims.[24] Two models can be used to estimate the distribution of instantaneous rates for a year based on climatic data at individual locations, however one is actually a refinement over the other. The original model, developed by

31. Dougherty, H. T., and Dutton, E. J. (1978) Estimating year-to-year variability of rainfall for microwave applications, IEEE Trans. Commun. COM-26(No. 8):1321-1324.

Rice and Holmberg, [17] was modified by Dutton et al [18, 19] and applied to a large number of locations in Europe and the U.S. to produce maps of rate versus percent of a year. Two models for estimating clock-hour distributions are also presented, but the use of these estimates with either the Davis and McMorrow, or Huschke models are not likely to produce better results than the Crane, Dutton-Dougherty, or Rice-Holmberg models.

The precision of distributions of instantaneous rates, whether derived from actual data or from an empirical model, is limited by instrument error and poor resolution of recordings down to 1 min. The combination of errors is likely in excess of 10 percent. Furthermore, the models we have presented estimate distributions to be expected on average at a point, but year-to-year variations in instantaneous distributions at a location can be quite large. This is discussed in Section 6 and should be considered in design problems for which a low risk is important.

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